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Coherence and Time-Delay Estimation for Sonar and Dual-Use Applications

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Reprint of a presentation made at the *Fourier Euroworkshop on Advanced Signal Processing*, 10-13 April 2000, Corfu, Greece.

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Coherence and Time-Delay Estimation for Sonar and Dual-Use Applications

A Presentation Made at the
Fourier Euro Workshop
Corfu, Greece

10-13 April 2000

Presented by:
Dr. Cliff Carter
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Portions presented to NATO ASI,
Il Ciocco, Italy, 11 July 1998.

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Outline

- Purpose
- Applications
- Environment
- Sensors
- Processing
- Processors
- Displays
- Performance
- Future
- Summary
- Questions

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Purpose of Talk

- Provide an overview of some of the signal processing techniques (including Coherence and Time-Delay Estimation that use Fourier Transforms) for underwater acoustic applications
- Stimulate thinking, experiments, and tests of technology developed for underwater acoustics for dual-use in other fields including bio-medicine, commercial fishing, fish monitoring and treaty compliance

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Selected Underwater Acoustic Applications

- Detection: Deciding if an object is present or absent
- Classification: Deciding the class or group of an object
- Localization: Measuring range, bearing, and depth
- Navigation: Determining, and controlling, position
- Communications: Transmitting and receiving acoustic information
- Control: Using a sound-activated release mechanism
- Position Marking: Beacons or Transponders
- Depth Sounding: Sending short pulses and timing bottom return
- Acoustic Speedometers: Using pairs of transducers to obtain speed

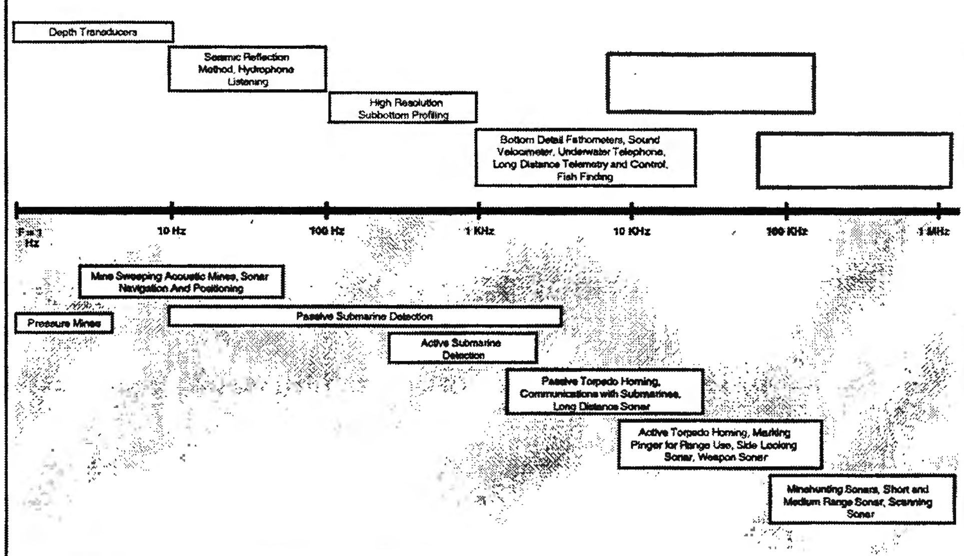
Source (modified): R.J. Urick, *Principles of Underwater Sound*, McGraw-Hill, New York, 1983.

Commercial Applications

- Fish Finders / Fish Herding
- Subbottom Geological Mapping
- Fish Population Estimation
- Environmental Monitoring
- Oil and Mineral Explorations
- River Flow Meter / Bathyvelocimeter
- Acoustic Holography
- Emergency Telephone
- Viscosimeter / Seismic Simulation and Measurement
- Acoustic Ship Docking System
- Ultrasonic Grinding / Drilling
- Sonar Calibration
- Biomedical Ultrasound (Active sonar)

Source (modified): R.J. Urick, *Principles of Underwater Sound*, McGraw-Hill, New York, 1983.

Commercial Applications



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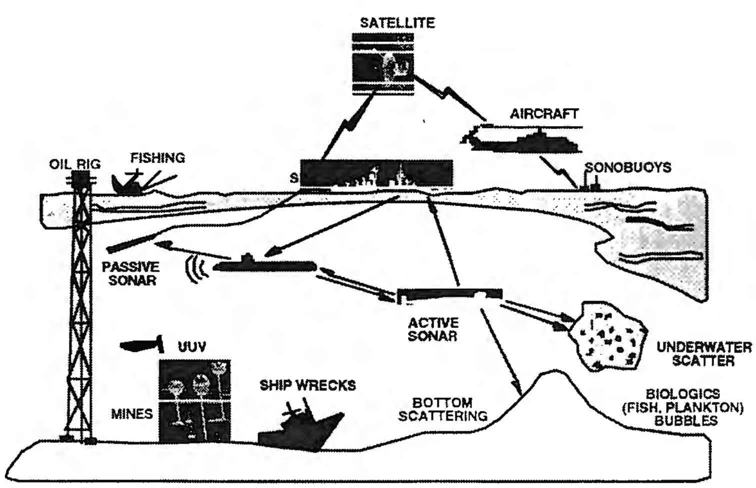
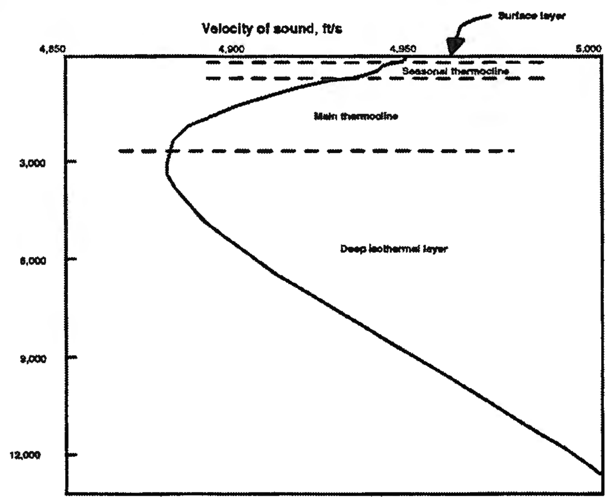
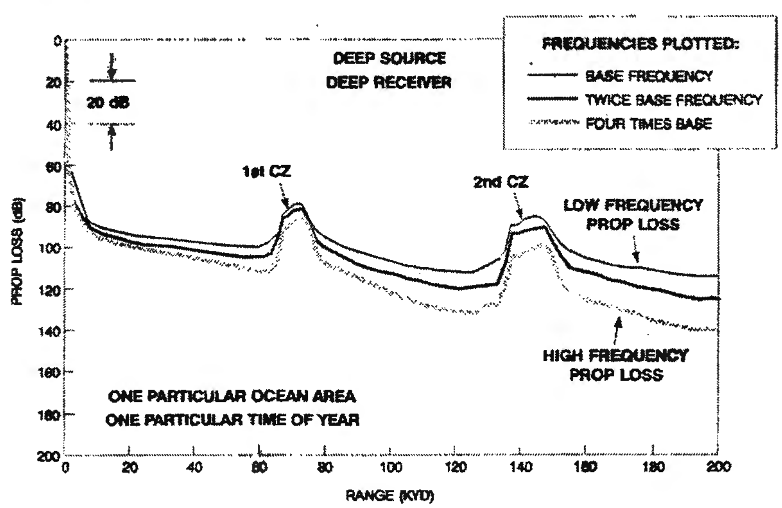
The Underwater Acoustic Environment



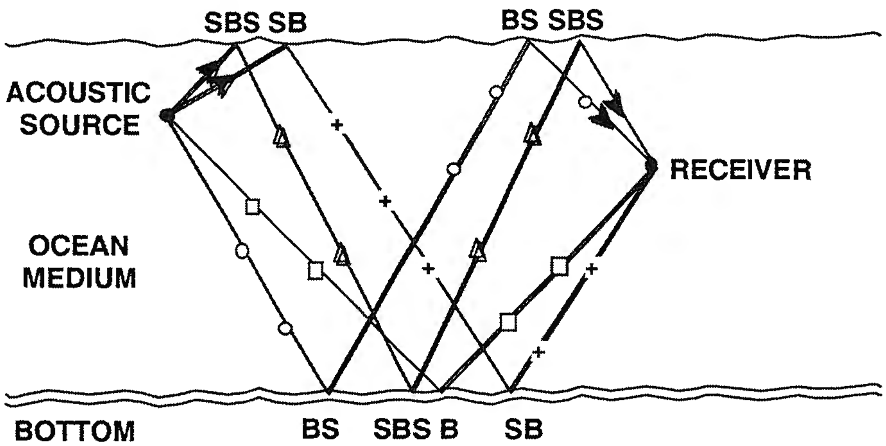
Sound Velocity Profile (SVP)
(one selected example)



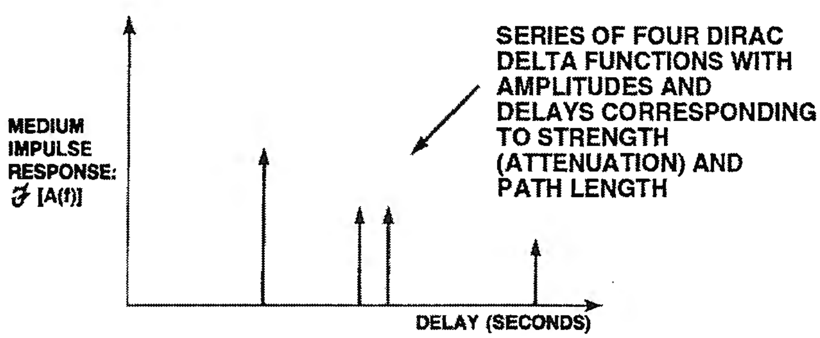
Artist's Sketch of Propagation Loss



Dominant Ray-Trace Paths
(beyond direct path and inside the first CZ)



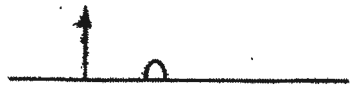
Medium Impulse Response
(Fourier Transform of Ocean Transfer Function)



Notational Cross-Correlation

(From pulsed source, 2 ray-path model)

CONSIDER A SINGLE PULSED SOURCE



AT RECEIVER #1 WE RECEIVE

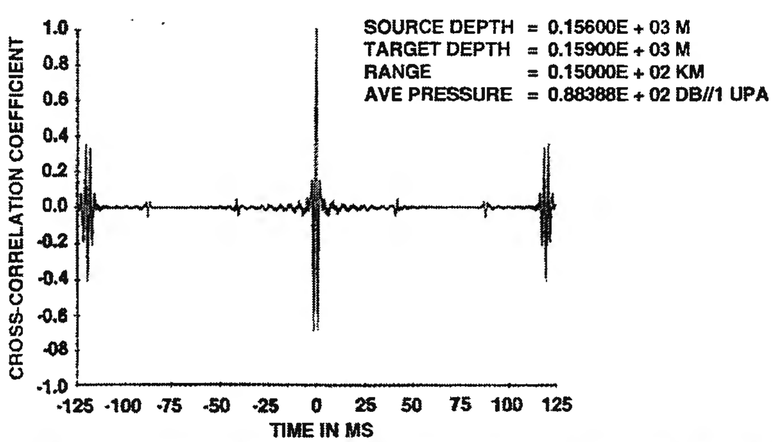
AT RECEIVER #2 WE RECEIVE

WHEN WE CROSS CORRELATE WE MAY GET

Cross-Correlation Coefficient vs Time Delay at Broadside

Target Range = 15 Km

Below-layer Case



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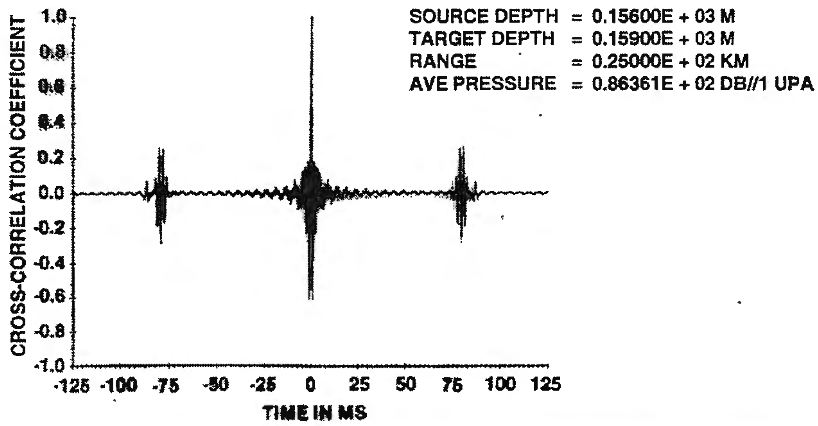
Cross-Correlation Coefficient vs Time Delay at Broadside

Target Range = 25 Km

Below-layer Case



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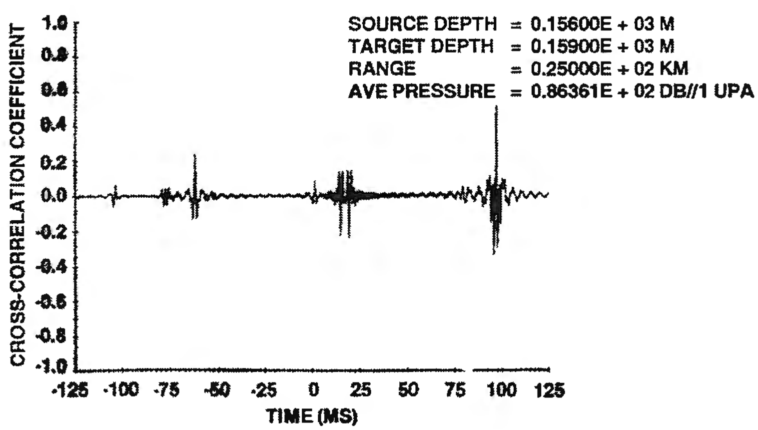
Cross-Correlation Coefficient vs Time Delay at 30 Degrees

Target Range = 25 Km

Below-layer Case



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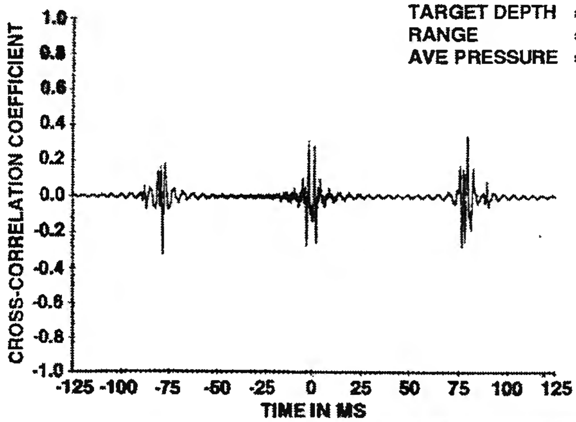
Cross-Correlation Coefficient vs Time Delay at Broadside

Target Range = 25 Km
Vertical Receiver Separation = 5 M
Below-layer Case

SOURCE DEPTH = 0.15600E + 03 M
TARGET DEPTH = 0.15650E + 03 M
RANGE = 0.25000E + 02 KM
AVE PRESSURE = 0.85910E + 02 DB//1 UPA



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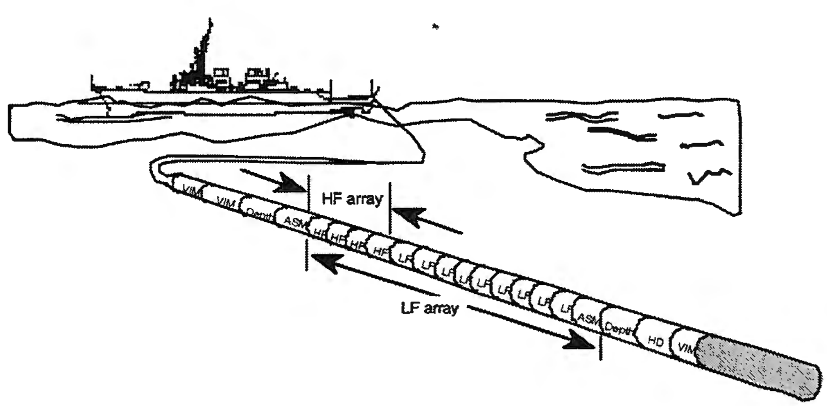
Artist Depiction of Towed Streamer

(passive sonar and active receiver for oil exploration)



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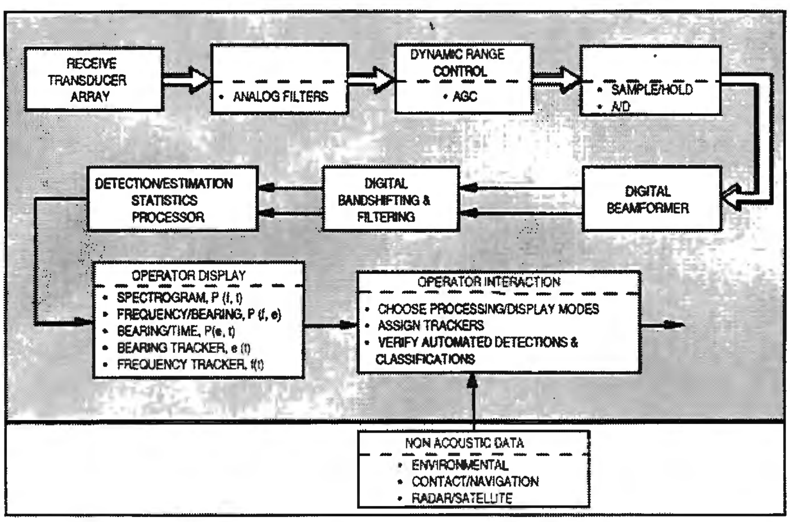
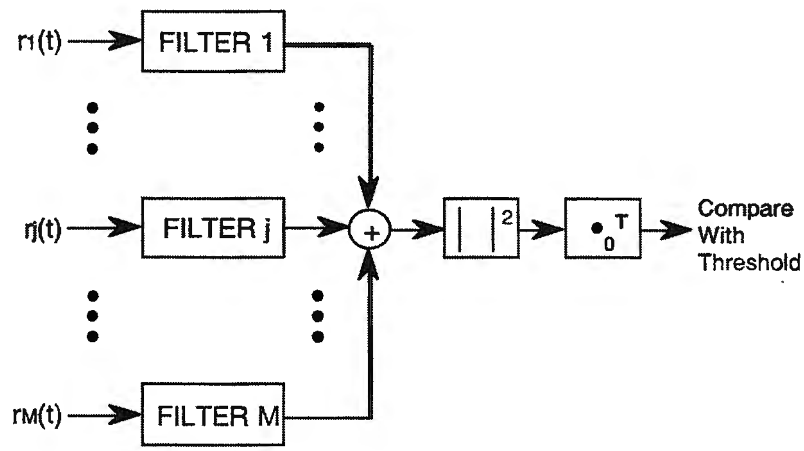
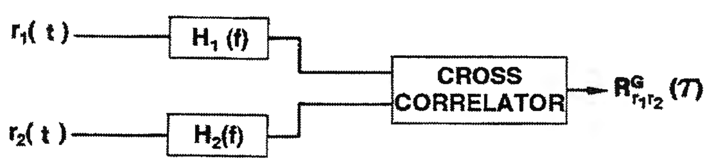
Conceptual Processing Chain



Energy Detector



GCC Approach for TDE



GCC FUNCTION

$$R^G_{r_1r_2}(\tau) = \int_{-\infty}^{\infty} W(f)\, G_{r_1r_2}(f)\, e^{j2\pi f\tau}\, df = \int_{-\infty}^{\infty} W_{\phi}(f)\, e^{j\phi(f)}\, e^{j2\pi f\tau}\, df$$

WEIGHTING FUNCTION

$$W(f) = H_1(f)\, H_2^*(f), \quad W_{\phi}(f) = |G_{r_1r_2}(f)|\, W(f)$$

GCC = Generalized Cross-Correlation
GCC = Fourier Transform of Weighted Cross Power Spectrum
TDE = Time Delay Estimation

Common Weighting Functions

METHOD	$W(f) = H_1(f)\, H_2^*(f)$	$W_\phi(f) = W(f)\, \lvert G_{r_1r_2}(f) \rvert$
SCC	1	$\lvert G_{r_1r_2}(f) \rvert$
ROTH	$1/G_{r_1r_1}(f)$	$\lvert G_{r_1r_2}(f) \rvert / G_{r_1r_1}(f)$
WIENER PROCESSOR	$C_{r_1r_2}(f)$	$C_{r_1r_2}(f)\, \lvert G_{r_1r_2}(f) \rvert$
SCOT	$1/\sqrt{G_{r_1r_1}(f)\, G_{r_2r_2}(f)}$	$\sqrt{C_{r_1r_2}(f)}$
PHAT	$1/\lvert G_{r_1r_2}(f) \rvert$	1
ML	$\dfrac{C_{r_1r_2}(f)}{[1 - C_{r_1r_2}(f)]\lvert G_{r_1r_2}(f) \rvert}$	$\dfrac{C_{r_1r_2}(f)}{1 - C_{r_1r_2}(f)}$

$$C_{r_1r_2}(f) = \frac{\lvert G_{r_1r_2}(f) \rvert^2}{G_{r_1r_1}(f)\, G_{r_2r_2}(f)}$$

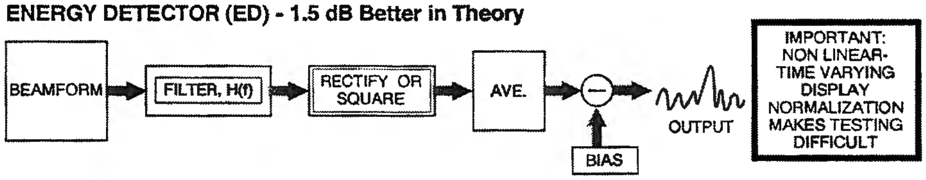
Filter Options

FILTER NAME	FREQUENCY DEPENDENCE, $H(f)\, H^*(f)$
STANDARD CC	1
ECKART (LOW SNR)	$S(f) / N^2(f) \rightarrow 1 / N(f)$, for (S=N)
PHAT	$1 / S(f)$
SCOT	$1 / [S(f) + N(f)] \rightarrow 1 / N(f)$ (LOW SNR)
ECKART (HIGH SNR)	$1 / [2N(f)]$

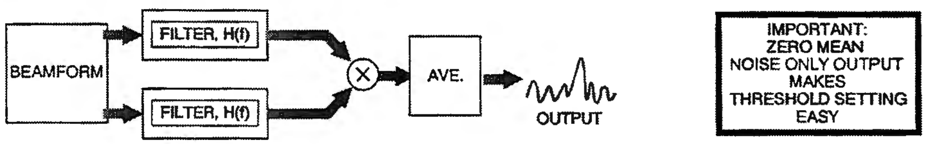
ECKART OPTIMUM IN THEORY;
SCOT/PHAT ADAPTIVE RESULTS ENCOURAGING;
NOISE AND SIGNAL SPECTRA MUST BE KNOWN OR ESTIMATED

ED vs. GCC

ENERGY DETECTOR (ED) - 1.5 dB Better in Theory



GENERALIZED CROSS-CORRELATOR (GCC) - Better in Practice



FOCUSED AND MATCHED BEAMFORMERS MAKE RAPID LOCALIZATION POSSIBLE

ROLE OF FILTERS TO BE DISCUSSED

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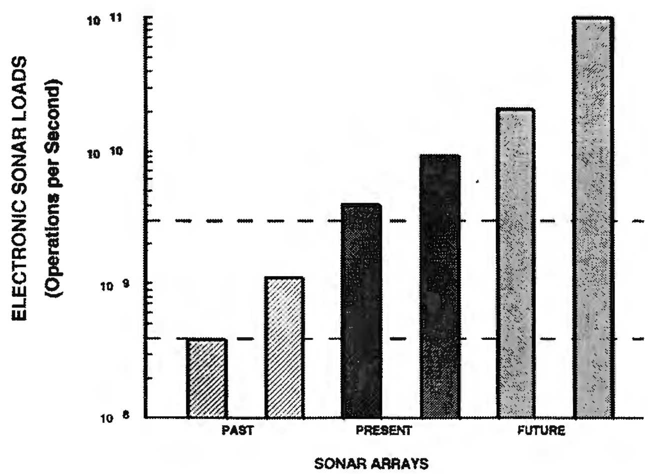
Projected Processing Load



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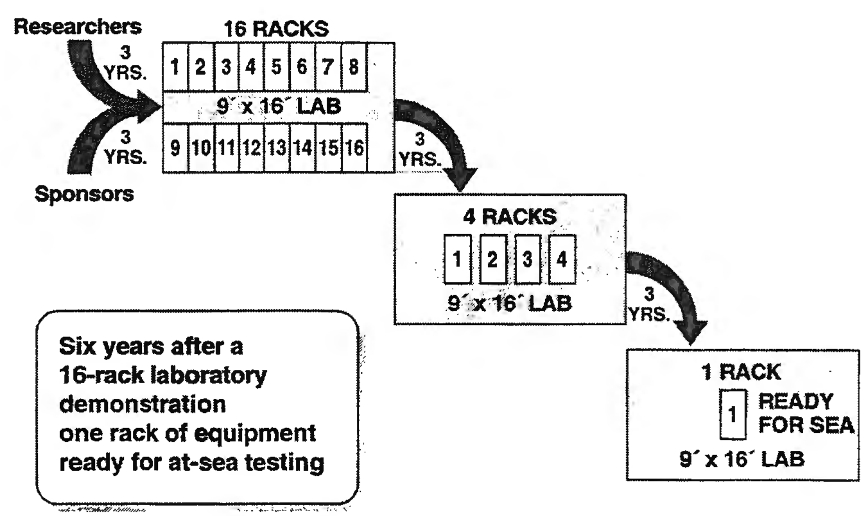
Implications of Moore's Law



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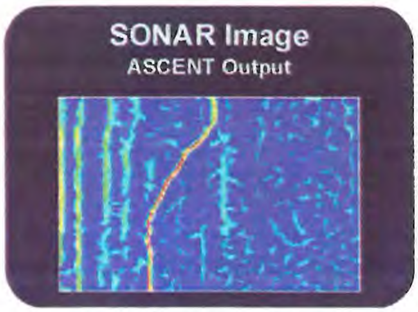
Notional FAST CNS BTR Display

Preliminary Results of Applying ASCENT Algorithm to Bearing-Time Recorder (BTR) Data

Time



Bearing

Results with Dr. Finkel, UPENN demonstrate full automation of visual display of acoustic data

- Modeled after the human visual processing system
- ASCENT extracts salient contours from a real BTR display

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Measuring Sonar Performance

SONAR FUNCTIONS	SONAR TEST METRICS (FUNCTIONS OF TIME AND SNR)
DETECTION / CLASSIFICATION	ROC, DEFLECTION d, RANGE ADVANTAGE, ARRAY GAIN, INITIAL DETECTION TIME, HOLDING TIME
LOCALIZATION (RANGE, BEARING, DEPTH)	BIAS, VARIANCE, $MSE = BIAS^2 + VAR$

RYJ 7056

The Sonar Equation

For passive sonar,

$$FOM_P = L_S - (L_N - N_{DI}) - N_{RD.}$$

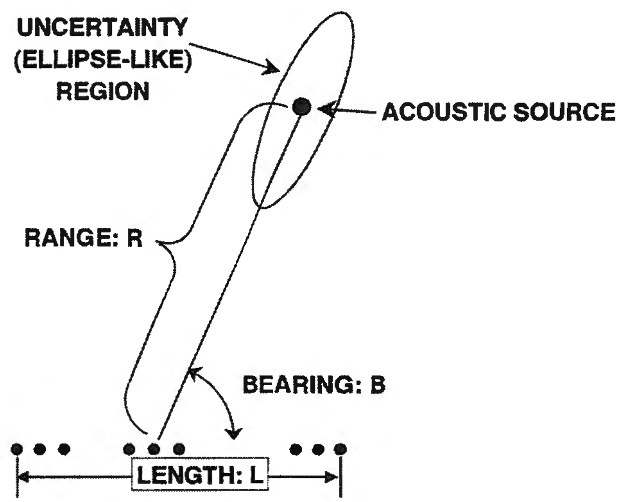
For active sonar,

$$FOM_A = (L_S + N_{TS}) - (L_N - N_{DI}) - N_{RD}$$

Array Gain

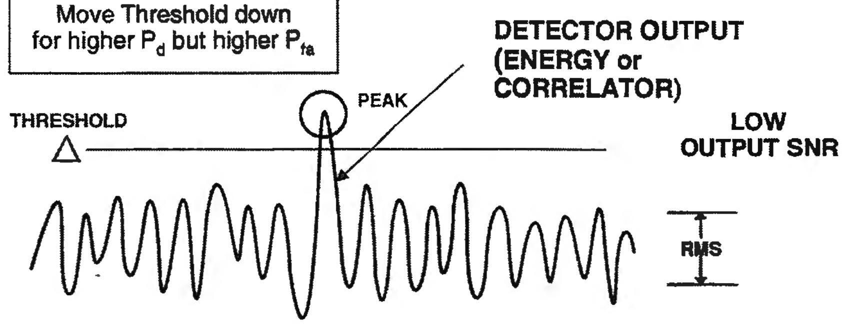
- In the simplest case, the increase in SNR due to the beamformer, called the *array gain* (in dB), is given by
  - $10 \log_{10}$ (The Number of Sensors)
- More Generally it is
  - AG = SG - NG

Passive Sonar Uncertainty



Deflection Criterion

Move Threshold down for higher P_d but higher P_{fa}



$$\text{DEFLECTION} = \frac{\text{PEAK}}{\text{RMS}}$$

Nonlinear changes to the peak can distort the deflection metric

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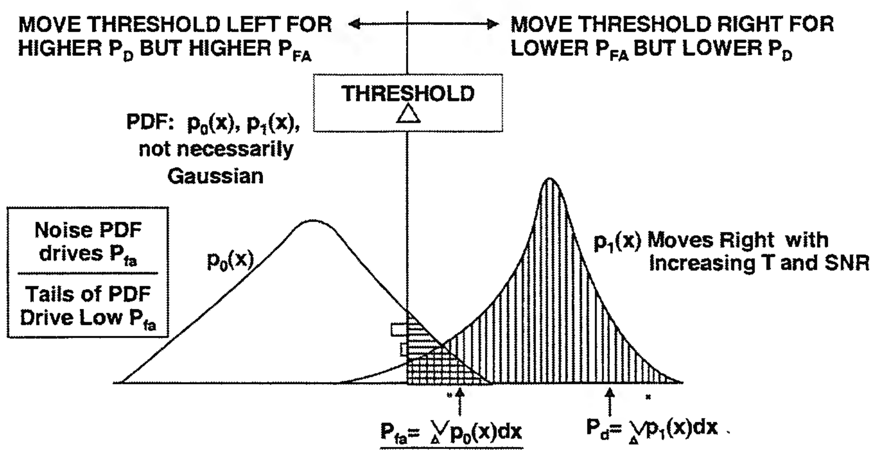
Computing ROC Curves
(For One System)



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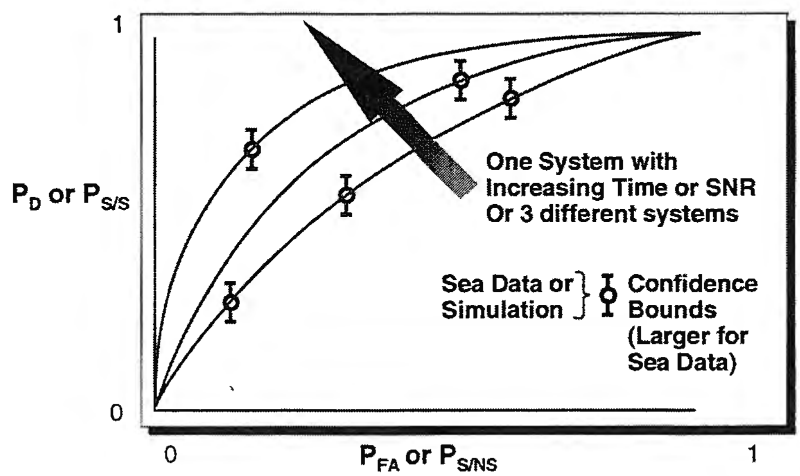
ROC Curves
(Either Testing Validates Theoretical Curves or Curves Connect Simulated Data Points)



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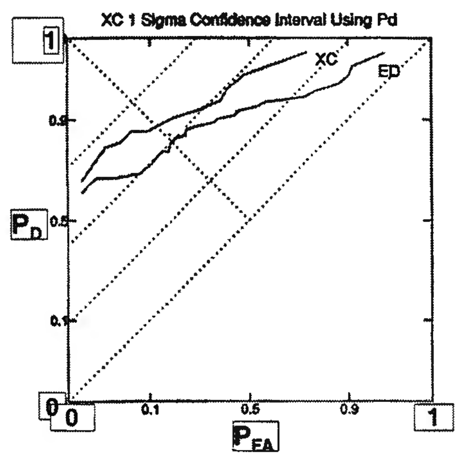
Example ROC Curves



(PRELIMINARY TEST RESULTS FROM V. PREMUS, MIT/LL)

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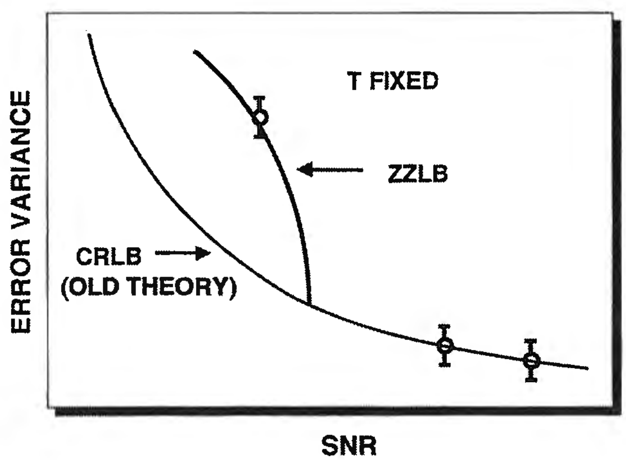
Variance vs SNR
Tighter Bounds Using ZZLB



No Sonar Can Do Better Than Lower Bounds

Error Variance Decreases By Increasing Time, SNR, & Array Length

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Human Brains

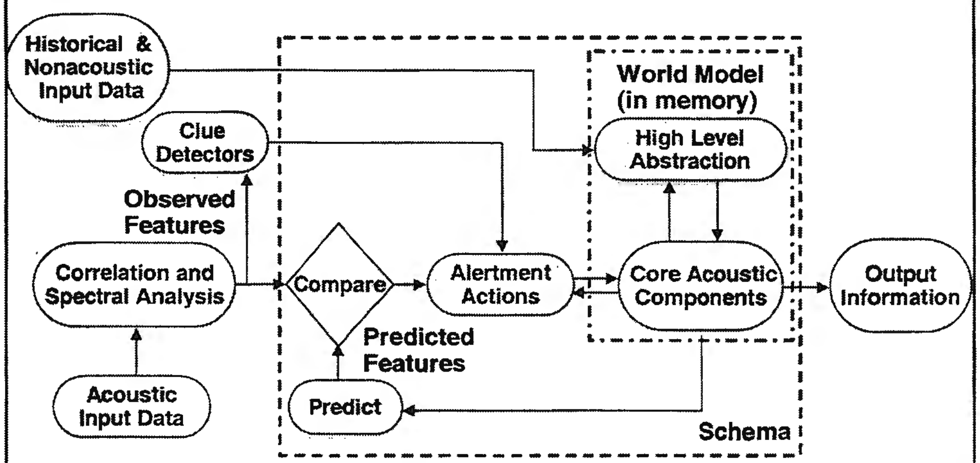
- Process acoustic signals with reasoning and learning
- Are systems with (sensory) inputs and (motor) outputs
- Are complex systems that are nonlinear and time-varying
- Have short-term and long-term memory organized with schema based world model
- Have slowly-changing architectures (synaptic plasticity)
- Have automatic (subconscious) and controlled (conscious)
- Can nonlinearly redirect attention in response to stimulation
- Have a massively parallel architecture with extensive feedback
- Contain 10 - 100 billion neurons
  - with 1,000 - 10,000 connections to other neurons
  - with nonlinear and time-varying
  - with sub-neuron microtubule structure
- Show evidence of resonating at 40 Hz
- Form biological inspiration for useful computational models

Our Vision

A Revolutionary
Fully Automated System Technology (FAST)
Cognitive Neuroscience (CNS) System that will:

- **Replace human operators with fully automated "silicon-based" assistants that recommend timely decisions with expert or "ace" abilities to a human machine supervisor**
- **Perform well in new acoustic environments**
- **Handle an order of magnitude more acoustic data**
- **Fuse, compress, & merge data into information**
- **Display needed information in the right format, to the right decision maker, at the right time**
- **Adapt to new tasks by learning & reasoning**

Prediction Driven Element of a CNS Sonar Architecture



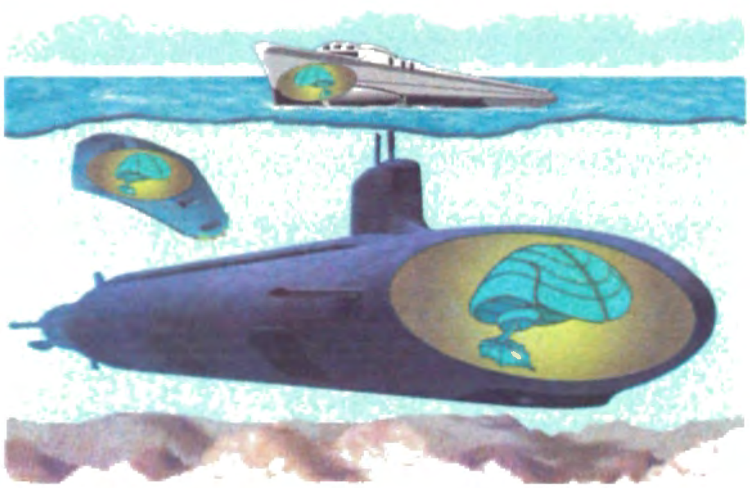
Note use of feedback, memory, alertment, and world model

Modified from Ellis, 1996 MIT Ph.D. Thesis

Open FAST CNS Questions

- How do we test & evaluate
  - a complex time-varying, nonlinear system?
  - learning, reasoning, and adaptability?
- What extensions are required to build a FAST CNS system?
- How to demonstrate a FAST CNS system?
- How does the internal architecture change with time?
- Is problem scalable? Is a CNS system demonstrable in small system? Or does it take a large system? How many neurons should be in the first phase test bed system system?
- What are appropriate architectures for our CNS system?
- How will we "program" our CNS system?
- How will our CNS system learn?
- How and at what data rates will we stimulate system?
- How does our CNS system implement the subconscious (automatic) and conscious (controlled) mind?

FAST CNS Sonar Systems



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Summary

- Provided an overview including Fourier based Coherence and Time Delay Estimation signal processing methods and their performance
- Discussed a FAST CNS Future view
- Stimulated thoughts on dual-use application of Fourier based Coherence and Generalized Cross-Correlation Smoothed Coherence Transform to bio-medicine, commercial fishing, fish monitoring and treaty compliance

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Questions

- Now
- at the break, or
- C.Carter@IEEE.org